OFFICE OF NAVAL RESEARCH

END-OF-THE-YEAR REPORT

PUBLICATIONS/PATENTS/PRESENTATIONS/HONORS/STUDENTS REPORT

for

GRANT or CONTRACT: N000149410302

PR NUMBER: 98PR01630-00

"Organized Nanorod-Superconductor Composites"

Charles M. Lieber
Principal Investigator

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Contract/Grant Title: "Organized Nanorod-Superconductor Composites"
Principal Investigator: Charles M. Lieber
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a. • Number of papers submitted to refereed journals, but not published: 1
b. • Number of papers published in refereed journals (for each, provide a complete citation): 5
c. • Number of books or chapters submitted, but not yet published: 0
d. • Number of books or chapters published (for each, provide a complete citation): 0
e. • Number of printed technical reports/non-refereed papers (for each, provide a complete citation: 0
f. • Number of patents filed: 3
g. • Number of patents granted (for each, provide a complete citation): 0
h. • Number of invited presentations (for each, provide a complete citation): 21
i. • Number of submitted presentations (for each, provide a complete citation): 0
j. • Honors/Awards/Prizes for contract/grant employees (list attached): 2
k. • Total number of Full-time Equivalent Graduate Students and Post-Doctoral associates supported during this period under PR project number: 3

Graduate Students: 3
Post-Doctoral Associates: 0

including the number of:

Female Graduate Students: 1
Female Post-Doctoral Associates: 0

the number of

Minority Graduate Students: 0
Minority Post-Doctoral Associates: 0

and the number of

Asian Graduate Students: 2
Asian Post-Doctoral Associates: 0

l. • Other funding (list agency, grant title, amount received this year, total amount, period of performance and a brief statement regarding the relationship of that research to your ONR grant).

• Use the letter and an appropriate title as a heading for your list, e.g.:
b. Published Papers in Refereed Journals, or, d. Books and Chapters published.
Also submit the citation lists as ASCII files via email or via PC-compatible floppy disks.

• Minorities include Blacks, Aleuts, AmIndians, Hispanics, etc. NB: Asians are not considered an under-represented or minority group in science and engineering.

a. • Number of papers submitted to refereed journals, but not published: 1

1. C.M. Lieber, "One-Dimensional Nanostructures: Chemistry, Physics & Applications", *Solid State Communications* (1998).

b. • Number of papers published in refereed journals: 5

1. P. Yang and C.M. Lieber, "Columnar defect formation in nanorod/$Tl_2Ba_2Ca_2Cu_3O_z$ superconducting composites, *Appl. Phys. Lett.* **70**, 3158-3160 (1997).

2. M.R. Eskildsen, P.L. Gammel, B.P. Barber, A.P. Ramirez, D.J. Bishop, N.H. Andersen, K. Mortensen, C.A. Bolle, C.M. Lieber, and P.C. Canfield, "Structural Stability of the Square Flux Line Lattice in YNI_2B_2C and $LuNi_2B_2C$ Studied with Small Angle Neutron Scattering", *Phys. Rev. Lett.* **79**, 487-490 (1997).

3. C.M. Lieber and P. Yang, "High-Temperature Superconductors", *Science* **277**, 1909-1910 (1997).

4. E.W. Wong, P.E. Sheehan and C.M. Lieber, "Nanobeam Mechanics: Elasticity, Strength and Toughness of Nanorods and Nanotubes", *Science* **277**, 1971-1975 (1997).

5. P. Yang and C.M. Lieber, "Nanostructured high-temperature superconductors: creation of strong-pinning columnar defects in nanorod/superconductor composites", *J. Mater. Res.* **12**, 2981-2996 (1997).

f. • Number of patents filed: 3

1. C.M. Lieber and P. Yang, "Metal Oxide Nanorods," 08/606,892, patent pending.

2. C.M. Lieber and E.W. Wong, "Preparation of Carbide Nanorods", 08/814,745, patent pending.

3. C.M. Lieber and P. Yang, "Method of Producing Metal Oxide Nanorods", 08/790,824, patent pending.

h. • Number of invited presentations: 21

1. "Structural Studies of Vortex Matter: What Can We Learn?", Institute for Theoretical Physics International Workshop on Vortex Matter in High-Temperature Superconductors, Ascona, Switzerland, June 1997.

2. "New Concepts in Nanofabrication", Cambridge Healthtech Institute's Nanotechnology: Materials, Manufacturing and Applications Conference, San Francisco, CA, June 1997.

3. "One-Dimensional Nanostructures: Rational Synthesis, Novel Properties and Higher Order Structures", Gordon Research Conference on Inorganic Chemistry, Newport, RI, July 1997.

4. "One-Dimensional Nanostructures: Synthetic Approaches and Physical Properties", Gordon Research Conference on Clusters, Nanocrystals & Nanostructures, Plymouth, NH, July 1997.

5. "Nanorod-Superconductor Composites: Nanostructured Materials with High Critical Current Densities", International Cryogenic Materials Conference, Portland, OR, July 1997.

6. "Nanostructured Superconducting Materials with Enhanced Critical Current Density", 1997 Cryogen Engineering & International Cryogen Materials Conference, Portland, OR, July 1997.

7. "Nanorod-Superconductor Composites: Nanostructured Materials with High Critical Current Densities", American Superconductor Corporation, Westborough, MA, August 1997.

8. "Growth, Structure and Properties of Carbide Nanorods", Norton/Saint-Gobain Industrial Ceramics, Inc., Northboro, MA, August 1997.

9. "One-Dimensional Nanostructures: Chemistry, Physics and Applications", University of Pennsylvania, Philadelphia, PA, October 1997.

10. "Growth and Physical Properties of One Dimensional Nanostructures", Michigan State University, East Lansing, MI, December 1997.

11. "One-Dimensional Nanostructures: Chemistry, Physics and Applications", James Franck Institute, The University of Chicago, Chicago, IL, December 1997.

12. "Nanostructures and Nanostructured Materials", 1998 American Association for the Advancement of Science Annual Meeting, Philadelphia, PA, February 1998.

13. "Synthesis of Nanostructures and Nanostructured Materials", Hutchinson Memorial Lecture, University of Rochester, Rochester, NY, February 1998.

14. "A Merger of Chemistry and Physics: Probing the Novel Properties of Nanotubes and Nanowires", Hutchinson Memorial Lecture, University of Rochester, Rochester, NY, February 1998.

15. "Probing Vortex Correlations in High-Tc Superconductors: Old and New Physics", Massachusetts Institute of Technology, Cambridge, MA, February 1998.

16. "Flux Line Lattice Structure at Large Scale with Weak Disorder", 1998 March Meeting of the American Physical Society, Los Angeles, CA, March 1998.

17. "Chemistry and Physics in 1D: Growth, Properties and Applications of Nanowires and Nanotubes", University of California at Los Angeles, Los Angeles, CA, April 1998.

18. "One-Dimensional Nanostructures: Novel Properties of Nanotubes and Nanowires", Department of Physics, University of California at Berkeley, Berkeley, CA, April 1998.

19. "Chemistry and Physics in 1D", Department of Chemistry, University of California at Berkeley, Berkeley, CA, April 1998.

20. "Chemistry and Physics in 1D: Synthesis, Properties and Applications of Nanostructures", Materials for the 21st Century and Beyond, 12th Annual Symposium of the Center for Study of Gene Structure and Function, Hunter College, New York, NY, April 1998.

21. "Rational Growth of Nanowires Using Laser-Generated Nanoclusters", Gordon Research Conference on Laser Interactions with Materials, Andover, NH, June 1998.

j. • Honors/Awards/Prizes for contract/grant employees: 2

1. Editorial Advisory Board, Advanced Materials, elected 1998.

2. Associate Member, International Union of Pure and Applied Chemistry, elected 1998.

l. • Other funding:

A. Agency: National Science Foundation
Grant Title: "Scanning Tunneling Microscopy Investigations of Low-Dimensional Materials."
Amount received this year: $150,000
Total Amount: $300,000
Period of Performance: 8/15/96 - 8/14/98

This grant has no direct overlap with the work of this ONR project.

B. Agency: Air Force Office of Scientific Research
Grant Title: "Nanotribology Investigations of Solid and Liquid Lubricants Using Scanned Probe Microscopies."
Amount received this year: $150,000
Total Amount: $450,000
Period of Performance: 11/1/96 - 10/31/99

This grant has no direct overlap with the work of this ONR project.

C. Agency: National Science Foundation (Materials Research Science and Engineering Center)
Grant Title: "Long-Range Order and Winding of Vortices in High-T_c Superconductors"
P.I.s: D.R. Nelson and C.M. Lieber
Amount received this year: $25,000
Total Amount: $25,000
Period of Performance: 3/1/98 - 8/31/98

This grant has no direct overlap with the work of this ONR project.

D. Agency: National Science Foundation (Materials Research Science and Engineering Center)
Grant Title: "Synthesis of Superhard Carbon Nitride Materials"
P.I.s: C.B. Agee, M.J. Aziz and C.M. Lieber
Amount received this year: $25,000
Total Amount: $25,000
Period of Performance: 3/1/98 - 8/31/98

This grant has no direct overlap with the work of this ONR project.

E. Agency: American Chemical Society - The Petroleum Research Fund
Grant Title: "Growth of 1-Dimensional Carbide Nanomaterials."
Amount received this year: $25,000
Total Amount: $50,000
Period of Performance: 1/1/97 - 8/31/99

This grant has no direct overlap with the work of this ONR project.

F. Agency: National Institutes of Health (subcontract from Brigham & Women's Hospital)
Grant Title: "Analysis of Alzheimer Amyloidogenesis with New Methods"
Amount received this year: $70,299
Total Amount: $92,576
Period of Performance: 6/1/97-5/30/99

This grant has no direct overlap with the work of this ONR project.

G. Agency: Department of Energy (subcontract from American Superconductor Corporation)
Grant Title: "MgO Nanorod HTS Composites"
Amount received this year: $53,484
Total Amount: $80,911
Period of Performance: 7/1/97-6/30/99

This grant has no direct overlap with the work of this ONR project.

PART II

a. Principle Investigator: Charles M. Lieber

b. Current telephone number: (617) 496-3169

c. Cognizant ONR Scientific Officer: Dr. John C. Pazik

d. Program objective:

The overall goal of this project is to develop rational approaches for controlling the nanostructure of high-temperature superconductors (HTSs) and other complex solids. Our emphasis on the nanometer scale is motivated by the recognition that control of structure in this size regime leads in general to materials with enhanced and/or novel electrical, thermal, mechanical, optical and magnetic properties. In this regard, our main objective has been to control the nanometer scale defect structure in HTSs to enhance critical currents. The intrinsic problem of thermally-activated flux flow, which limits critical currents in all HTS materials, can be reduced significantly by creating nanometer diameter columnar defect structure in the HTSs. Specific objectives that have been pursued during the past year include (1) the design of a large scale synthesis of MgO nanorods that function as columnar defects in HTSs, (2) elucidation of factors critical to the creation of a well-defined nanorod/HTS nanostructure in bulk materials, and (3) the development of general approaches to the synthesis of nanowires of other materials.

e. Significant results during last year:

A number of significant results have been obtained during the past year of this project, including: (1) the development of general synthetic methods to prepare MgO nanorods; (2) the preparation of MgO nanorod/HTS bulk composites with HTS = $Bi_2Sr_2CaCu_2O_8$ (BSCCO-2212) and $Bi_2Sr_2Ca_2Cu_3O_{10}$ (BSCCO-2223); (3) the discovery and elucidation of a novel self-organization process whereby MgO nanorods self-align in orientations perpendicular and parallel to the copper oxide planes; (4) the development of a new and general synthetic approach for the growth of nanowires. These results have significant impact in several ways. Our proof-of-concept experiments with the MgO nanorod/ BSCCO-2212 and BSCCO-2223 system have elicited significant interest by the major HTS wire manufacturers in the United States and Japan, and have led to a collaborative scale-up effort with American Superconductor Corporation. In addition, the general approaches developed in this project for the growth of nanowires and self-organized nanostructured materials are expected to impact critical areas such as thermoelectrics.

f. Brief summary of plans for next years work:

The major goals of this project for the coming year are as follows. We plan to develop significantly the synthesis and understanding of bulk nanorod/BSCCO materials (2212 and 2223), since these systems may have the largest impact on technology. Effort will be placed on developing efficient syntheses of MgO nanorods, dispersing the nanorods uniformly in BSCCO matrices, and characterizing and optimizing nanostructure in these materials. We also plan to pursue the fabrication of ordered arrays of nanowires, and to develop further and explore the new concepts of nanowire growth and self-organized nanostructured materials that are emerging from this project.

g. List of names of graduate students and post-doctoral(s) currently working on project:

1. Qingqiao Wei
2. Latha Venkataraman
3. Xiangfeng Duan

Principle Investigator: Charles M. Lieber

Project Title: "Organized Nanorod-Superconductor Composites"

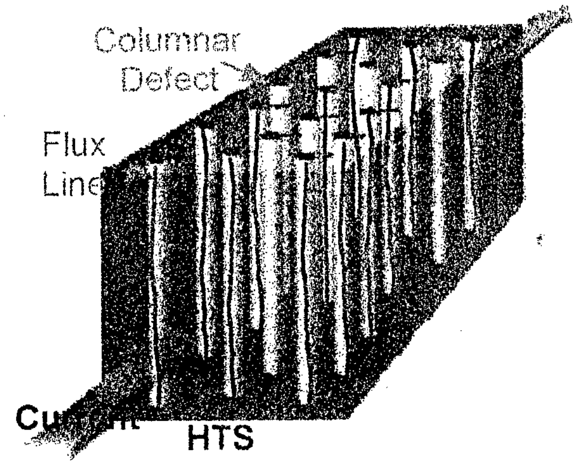
Cognizant ONR Scientific Officer: Dr. John C. Pazik

Highlights of Research Project: 6/97 - 6/98

Nanostructured High Temperature Superconductors

Technology Issues: the critical current density impacts all HTS application areas: power transmission; motors; magnets; key issues are HTS structure and defects

Objectives: prepare 1-dimensional (1D) nanorods; prepare & characterize bulk nanorod/HTS composites and wires;develop general methods for growth of nanowires and nanostructured materials



Approach:

- create nanostructured HTS materials with columnar defect structure
- use chemically compatible 1D nanorods within HTS matrix
- develop rational methods for growth of 1D structures

Accomplishments:

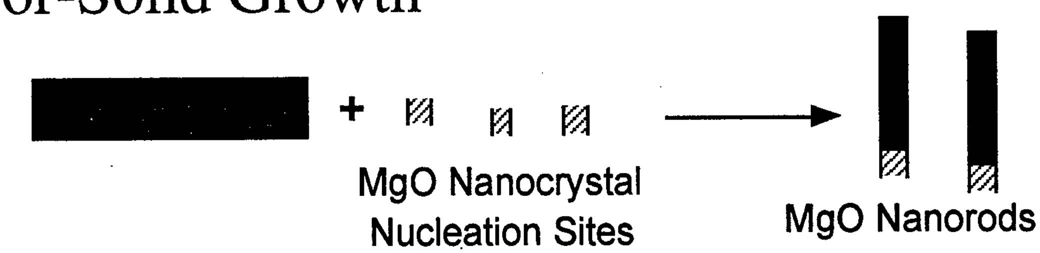
- MgO nanorods with required structure, chemical reactivity and anisotropy synthesized
- bulk nanorod/HTS superconductor composites prepared with enhanced critical currents
- general approach for nanowire growth developed

Impact & Transition

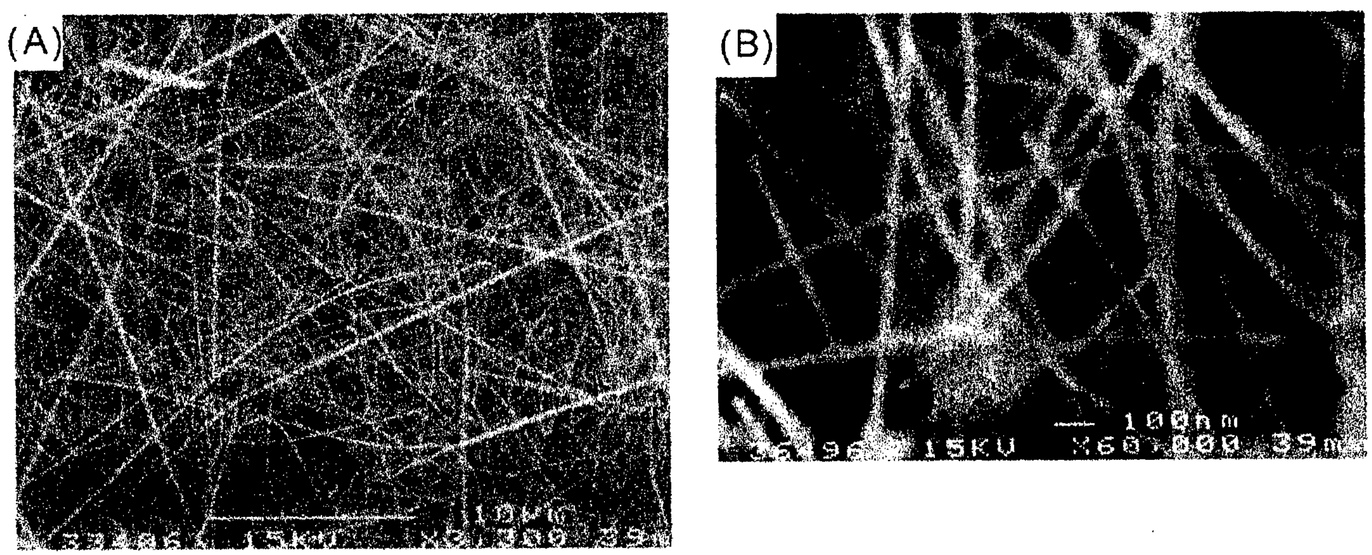
- nanorod/HTS S&T scale-up collaboration with American Superconductor Corporation
- new and general approaches for nanowire growth and rational assembly of nanostructured materials

Bulk Synthesis of MgO Nanorods

- Vapor-Solid Growth

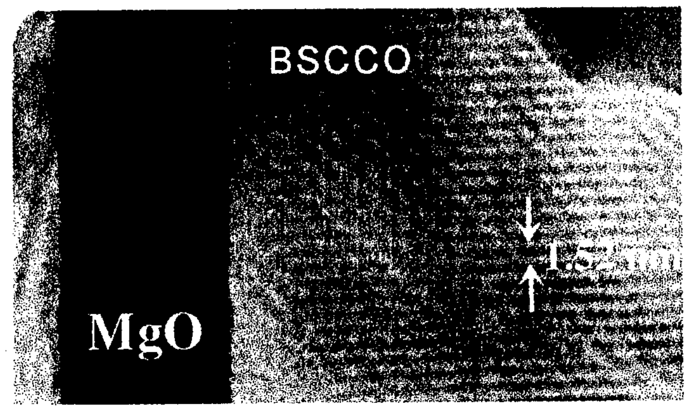


- MgO Nanorods



Nanostructured Bulk HTS Materials

- BSCCO-2212



- BSCCO-2223